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Article *in* Physics in Perspective · December 2002
DOI: 10.1007/s000160200002

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Phys. perspect. 4 (2002) 399–420
1422–6944/02/040399–22

Physics in Perspective

C. V. Raman and the Discovery of the Raman Effect*

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In 1928 the Indian physicist C. V. Raman (1888–1970) discovered the effect named after him virtually simultaneously with the Russian physicists G. S. Landsberg (1890–1957) and L. I. Mandelstam (1879–1944). I first provide a biographical sketch of Raman through his years in Calcutta (1907–1932) and Bangalore (after 1932). I then discuss his scientific work in acoustics, astronomy, and optics up to 1928, including his views on Albert Einstein's light-quantum hypothesis and on Arthur Holly Compton's discovery of the Compton effect, with particular reference to Compton's debate on it with William Duane in Toronto in 1924, which Raman witnessed. I then examine Raman's discovery of the Raman effect and its reception among physicists. Finally, I suggest reasons why Landsberg and Mandelstam did not share the Nobel Prize in Physics for 1930 with Raman.

Key words: Raman effect; Chandrasekhara Venkata Raman; Nobel Prize in Physics; light scattering; Arthur Holly Compton; Compton effect; light quanta; Albert Einstein; Arnold Sommerfeld; Adolf Smekal; Grigorii Samuilovich Landsberg; Leonid Isaakovich Mandelstam.

Introduction

In 1905 Albert Einstein (1879–1955) proposed his revolutionary hypothesis of light quanta, which in succeeding years was greeted by physicists with extreme skepticism. Max Planck (1858–1947) called it "a speculation that missed the target," and Robert A. Millikan (1868–1953) said it was a "bold, not to say reckless hypothesis."[1] It gained acceptance only after 1923, when Arthur Holly Compton (1892–1962) discovered the Compton effect,[2] the change in wavelength of an X-ray quantum when striking a free electron in a substance such as carbon in a billiard-ball collision process.

Five years after Compton's discovery, the Indian physicist Chandrasekhara Venkata Raman (1888–1970) and his student Kariamanikam Srinivasa Krishnan (1898–1961) discovered another effect involving a change in wavelength of scattered monochromatic visible light. Probably because of its generality, the American

* This article is based on a talk I gave on December 16, 2000, at a Symposium on the Foundations of Quantum Physics before 1935 in Berlin, Germany.

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physicist Robert Williams Wood (1868–1955), who was well known for his work in experimental optics, hailed their discovery with the words: "It appears to me that this very beautiful discovery, which resulted from Raman's long and patient study of phenomena of light scattering, is one of the most convincing proofs of the quantum theory of light which we have at the present time."[3] In this paper, I first provide a biographical sketch of Raman; I then discuss his scientific work before the discovery of the Raman effect; and I finally comment on the reception of his discovery by the scientific community at the time.

Chandrasekhara Venkata Raman

Chandrasekhara Venkata Raman (figure 1) was born on November 7, 1888, in a village near Trichinopoly in the province of Tamil Nadhu, India.[4] His father Chandrasekaran Aiyar was professor of mathematics and physics at the A.V.N. College in Vizagapatam; his mother Parvati Ammal came from an educated family known for its Sanskrit scholarship. Like his father, Raman played the violin

Fig. 1. Chandrasekhara Venkata Raman (1888–1970). Courtesy of the Raman Research Institute, Bangalore.

exceedingly well and was deeply interested in music and acoustics,[5] following in the venerable tradition of Lord Rayleigh (1842–1919) and Hermann von Helmholtz (1821–1894). In a symposium on *Books That Have Influenced Me* Raman recalled:

> Speaking of the modern world, the supremest figure, in my judgment is that of Hermann von Helmholtz … . It was my great good fortune, while I was still a student at college, to have possessed a copy of an English translation of his great work on "The Sensations of Tone." … It treats the subjects of music and musical instruments not only with profound knowledge and insight, but also with extreme clarity of language and expression. I discovered the book myself and read it with the keenest interest and attention. It can be said without exaggeration that it profoundly influenced my intellectual outlook. For the first time I understood from its perusal what scientific research really meant, and how it could be undertaken. I also gathered from it a variety of problems for research which were later to occupy my attention and keep me busy for many years.[6]

He continued: "Helmholtz had written yet another great masterpiece, 'The physiology of vision.' Unfortunately, this was not available to me as it had not then been translated into the English language." Raman dedicated the last epoch of his life to this topic and wrote a book of the same title.[7]

Raman studied at his father's college and at the Presidency College of the University of Madras, where he received his B.A. degree in 1904 at the age of 16, ranking first in his class and receiving a gold medal in physics. He received his M.A. degree with the highest honors in January 1907. Meanwhile, in 1906, he had published his first scientific paper, which was on diffraction and appeared in the *Philosophical Magazine*.[8] He carried out further researches as a student but they were not published for various reasons.[9] His teachers were greatly impressed with him, remarking: "The best student I have had in thirty years"; "A young man of independence and strength of character"; "Exhibited an unusual appreciation of English literature and a facility in idiomatic expression"; "Possessing great alertness of mind and is strong intellectual."[10] His physics professor, R. L. Jones, especially recognized Raman's aptitude for research and urged him to go to England for further studies. Jones sent him to Colonel Gifford for a physical checkup. Raman recalled that Gifford "examined me and certified that I was going to die of Tuberculosis … if I were to go to England."[11]

Raman's best choice for a good position was in the Indian Finance Department, for which he had to take a special examination. He recalled about his examiners in physics and economics: "I had such tremendous confidence in myself that I had not the least difficulty in putting those gentlemen in their proper places. I made it clear to Sir [Jagadis Chunder] Bose that I knew as much Physics as he did."[12] Such a mixture of self-confidence, pride, and arrogance were part of his personality.

Raman placed first in this examination, as he always had in the past, and was appointed as a bank officer in Calcutta in 1907. There he came into contact with the Indian Association for the Cultivation of Sciences (IACS), which had been established in 1876 for research purposes by Mahendralal Sircar (1833–1904). Raman became a member for life, and to make its work much better known, he took the lead in bringing out its *Bulletin* and *Proceedings*, the latter of which was renamed in 1926 as the *Indian Journal of Physics*. His own research and outstanding scientific abilities soon made him a popular figure among Calcutta's educated elite. Still, when the Palit Professorship of Physics at Calcutta University was established, Raman was not the first choice for this position. Asutosh Mookerjee (1864–1924), a judge and Vice Chancellor of Calcutta University, wrote to the Viceroy of India on June 29, 1912, that, "I am hoping to be able to secure Dr. J. C. Bose for the Chair of Physics … ."[13] This plan fell through for some reason, however, and in 1914 the Palit Professorship was offered to Raman.

Raman was reluctant to accept this position, because it carried a salary of only 600 rupees, about half of what he was making as a bank officer.[14] At this critical time, his wife Lokasundri (1892–1980), whom he had married in 1907, suggested that he should not bother about this financial question and should accept the professorship.[15] Before he did, he gave it careful consideration and imposed definite conditions on his acceptance. On May 11, 1917, a letter in which he presented his conditions was read at a meeting of the Syndicate of the University by its Secretary, who reported that Raman had received permission to accept the Palit Professorship and had requested to be informed if the University was prepared to sanction the following conditions:

> (a) House allowance of 250 rupees per mense [month] in addition to the salary for the chair, so long as a suitable residence is not provided, (b) to declare that his position in relation to teaching M.A. and M.Sc. students would be the same as has been defined and accepted in the case of … [others]; (c) to formally appoint him as Director of the Sir T. N. Palit Physical Laboratory to supervise and control the physics staff working in the laboratory and also to be in sole executive charge of all laboratory arrangements. Also suggested that a grant of 5000 rupees be placed at his disposal to enable him to arrange the first setting up of his research laboratory.[16]

Raman was not given full control of the laboratory, but all of his other conditions were met.

The available documents show that as soon as Raman assumed the Palit Professorship, conflicts arose. On August 30, 1917, Jagadis Chunder Bose (1858–1937), who was Professor of Physics at Presidency College, Calcutta, and was well known also for his work on plant physiology, wrote to the Vice Chancellor of Calcutta University:

> It has been reported to me that, on the 25th instant, a member of the Department of Physics of the University College of Science called at my Laboratory at the Presidency College during my absence, and with special instructions from Prof. Raman to invite my senior mechanic to transfer his services to the College of Science Physical Department, with offer of increased salary above what he gets from me … even up to three times if necessary … . I must, therefore, formally express to the University my regret … .[17]

There also are reports about a dispute that Raman had with the Indian astrophysicist Meghnad Saha (1894–1956) regarding the use of the laboratory.[18] Parochialism too played a role, with Raman being considered as an "outsider." For instance, in one of his letters Saha wrote to a student, Pratap K. Kichlu, that: "When you submit [your] thesis for [the] D.Sc. . . the examiners ought to be Professor [Ralph H.] Fowler, Lord Rayleigh and myself. Do not allow Raman or [John W.] Nicholson to be put in. It is time that the Committee of Courses in Physics should insist on an internal man."[19] On the whole, however, Raman's relations with other Bengalis, and in particular with Saha, remained collegial until 1933. In 1931, for example, Raman wrote a reasonably good Foreword to the first edition of Saha's book on heat.[20]

Raman's activities extended beyond Calcutta University. In 1914 the Indian Science Congress (ISC) was founded (it was renamed the ISC Association in 1935) on the model of the British Association for the Advancement of Science, and from 1915 to 1921 two of its founders, J. L. Simonsen and P. S. McMohan, who were British professors working in India, served as its secretaries, while subsequently Indian scientists like Raman and the plant morphologist Shankar P. Agharker (1884–1960) also held this position.[21] In 1919 Raman also became honorary secretary of the Indian Association for the Cultivation of Science (IACS),[22] and at the end of 1922 he was proposed for membership on the Council of the Asiatic Society of Bengal (founded in 1784 by William Jones) and was elected to it the following year.[23] Raman also held various positions in the Astronomical Society of India (see below).

Until 1917 Raman carried out his researches almost single-handedly. Then, after he became Palit Professor, he was allowed to use the Calcutta University laboratories, but he still worked mostly at the IACS. His researches on acoustics and optics brought him high recognition. In November 1921 he was proposed for election as a Fellow of the Royal Society of London. His nomination certificate reads:

> Although trained entirely in India, [Raman] has made considerable additions to our knowledge of sound and light, having published about fifty memoirs. The chief are: Experimental Investigations on the Maintenance of Vibration; The Dynamical Theory of Bowed Strings; Vibrations of Bowed Strings and of Musical Instruments of the Violin Family; On Kaufmann's Theory of the Pianoforte Hammer; … . Photometric Measurement of the Obliquity Factor of Diffraction; The Curvature of Lines in Diffraction Spectra; . . . The Diffraction Figures due to an Elliptic Aperture; The Colours of Mixed Plates.[24]

Raman was elected FRS on May 15, 1924.

The highest honor Raman received was the Nobel Prize in Physics for 1930 for his work on the scattering of light, particularly for his discovery of the effect named after him. In 1933 he accepted the directorship of the Indian Institute of Sciences (IIS) in Bangalore, evidently with some hesitation according to unpublished biographical documents of his predecessor, Sir Martin O. Forster, FRS (1872–1945). In Calcutta Raman was in the prime of his life and was feeling well; in Bangalore he soon became involved in both scientific and personal controversies. After 1933, three major incidents in his scientific life occurred that made him a controversial and bitter person. First, a group of people in Calcutta had the feeling that Raman, who was now living in Bangalore, still controlled the affairs of the IACS and wanted to change its constitution in regard to its provision for lifetime membership.

According to its statutes, any person who donated 500 rupees could become a member for life, whereas Raman wanted to place the decision for granting lifetime membership in the hands of a managing committee. Before Raman could change the constitution accordingly, word of his plan leaked out and was exploited by a local newspaper,[25] forcing Raman, who had been a member of the IACS for 25 years, to leave the Association in disgrace. Second, a committee was formed to explore the establishment of a scientific academy on the model of the Royal Society of London. Raman was one of the committee members, but before its final meeting he resigned and personally established the Indian Academy of Sciences in 1934,[26] which made him exceedingly unpopular in some circles. Third, owing to various disputes with the staff and members of the Council of the Indian Institute of Sciences (IIS) in Bangalore, he was forced to resign as its director in 1937.

After his resignation as director, Raman remained as Professor and Head of the Department of Physics of the IIS until his retirement in 1948. He then built a new institute for himself in a suburb of Bangalore (today it is known as the Raman Research Institute) where he worked with half a dozen students during the following decade, making significant contributions to the fields of crystal physics, crystal optics, and mineralogy. During the last ten years of his life he worked without any students or assistants.[27] He remained President of the Indian Academy of Sciences in Bangalore and Director of the Raman Research Institute until his death in 1970.

Raman's Scientific Work up to 1928

Raman as Palit Professor founded what became known as the Calcutta School of Physics. His scientific fame attracted students and researchers from all corners of India to work under him. As the Indian historian S. N. Sen noted, "During the year 1928, Prof. Raman had under him in the laboratories of the Association [IACS] 32 research workers, of whom 21 were whole-time workers and 11 worked part-time. The number of research workers in the Palit Laboratory of Physics at the [Calcutta] University College of Science is not known."[28] By 1938, a decade later, around 80 positions, mostly in universities and colleges, were occupied by Raman's former students or collaborators.[29] Prior to 1921, when his research took a new turn as we shall see, he and his students worked mostly in three fields, acoustics, astronomy, and optics.

Acoustics

Although Raman is known today mostly for his work on the scattering of light, he also carried out significant researches in acoustics. In a recent review of the non-linear physics of musical instruments, N. H. Fletcher wrote: "Musical instruments have been of interest to scientists from the time of Pythagoras, 2500 years ago, and since then many famous physicists, among them Helmholtz, Rayleigh and Raman, have devoted at least some of their attention to them."[30] That Raman was mentioned in the same breath with Helmholtz and Rayleigh leaves no doubt about the importance of his work. His researches on musical instruments have continued to attract attention in the 1990s.[31]

One of Raman's masterpieces was his monograph of 1918, "On the Mechanical Theory of the Vibrations of Bowed Strings and of Musical Instruments of the Violin Family."[32] Earlier, his work had attracted favorable attention both in England[33] and in Germany. Regarding the latter, S. N. Sen has observed that: "Raman's investigations on the maintenance of vibrations were noticed with appreciation by Prof. Alfred Kalähne ... in the Proceedings of the German Physical Society in the November issue of 1914 in connection with his review of Helmholtz's theory of forced vibrations of a string."[34] A dozen years later, Raman was the only non-European who was invited to contribute an article to the famous *Handbuch der Physik*.[35] His contribution, "Musikinstrumente und ihre Klänge" ("Musical Instruments and their Tones"), dealt with the physical characteristics of the musical tones emitted by string, wind, and percussion instruments.[36] In an earlier chapter in the same volume of the *Handbuch*, the work of Raman and his collaborators was cited extensively.[37]

Astronomy

Raman's interest in astronomy seems to have escaped the attention of his biographers. It was associated with the founding of the Astronomical Society of India (ASI) in 1910 in connection with the observation of Halley's Comet.[38] In 1911 Raman was elected as a member of the ASI, and he later held various offices in it, such as Secretary of Business, Honorary Secretary, and Director of the Variable Star Section.[39] He also delivered popular lectures at meetings of the ASI, which were published in the Society's journal, and which dealt with diffraction and interference phenomena in telescopes and astronomical observations he made with them.[40] Thus, he made observations of a lunar eclipse, of Venus, and of the satellites of Jupiter with a small telescope, and later with a somewhat larger one.[41] His name was carried as an elected member of the Council of the ASI until 1919–1920, although a study of the Society's journal reveals that his active work in astronomy ceased in 1916 for practical reasons,[42] namely, because he could not afford to purchase a powerful telescope and locate a proper site to make observations.[43]

Optics

Beginning in 1921, Raman began to concentrate on a new topic, optics, and during the next two years he published 42 papers on this subject, some with coauthors.[44] During 1922 most of his work was related to the scattering of light in liquids, vapors, and gases. His two major contributions that year were, first, writing a monograph, *Molecular Diffraction of Light*,[45] that summarized various work and, second, proposing an explanation of the blue color of the sea, which I will discuss below.

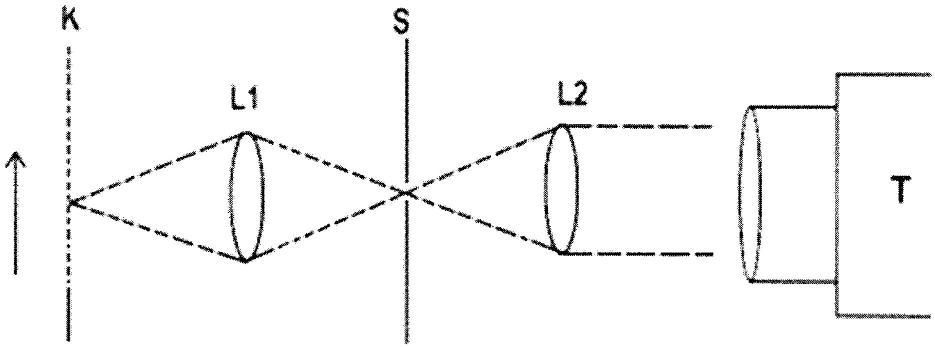

Fig. 2. Canal rays at K travel perpendicular to the optical axis of lens L1 and through one of its focal points, the other one being at a slit in the screen S. The light emitted by the canal rays then enters lens L2, is collimated, and enters telescope T.

In 1923 Raman turned to X-ray scattering, but during 1923–1924 he published only four papers on this subject and then interrupted this work for almost three years,[46] very likely because he realized that he needed expert help in this field. Thus, during this period he established contact with the Swedish experimental physicist Manne Siegbahn (1886–1978) and the Danish theoretical physicist Niels Bohr (1885–1962), asking them to take on one of his former students, Bidhu Bhushan Ray (1894–1944), and train him in this field.[47] Ray spent six months with Siegbahn in Uppsala and a year and a half with Bohr in Copenhagen (October 1924–February 1926).[48] After returning home, however, Ray and Raman for some reason went their separate ways, coauthoring no papers together.

Raman and Light Quanta*

Raman's first two publications that were directly related to Einstein's light-quantum concept appeared in 1922.[49] They were in response to Einstein's proposal in December 1921 of an experiment that should be able to decide between the wave and quantum natures of light.[50] Einstein's proposed experiment is illustrated in figure 2, where canal rays (positive ions) travel perpendicular to the optical axis of lens L1 and through one of its focal points, the other one being at a small slit in screen S. Thus, any light that is emitted by the canal rays passes through the slit in screen S, enters the lens L2, is collimated, and then enters the telescope T. Since the canal rays are moving, however, the light they emit, if it consists of waves, should be Doppler-shifted, and indeed in such a way that its wavelength when leaving lens L2 should be greater at the top of the beam than at the bottom. If a dispersive medium is then placed between lens L2 and the telescope T, the beam of light

* This and the following section are based largely on my article, "The Indian Trio: S. N. Bose, C. V. Raman and M. N. Saha, and the Light Quanta," in *International Symposium on the Centenary of Planck's Law: Relevance in Science and Technology* (Calcutta, December 14–16, 2000), pp. 25–39.

should be deviated slightly, so that the image of the slit as seen in the telescope should be shifted somewhat, by an amount that is proportional to the thickness of the dispersive medium. By contrast, if the canal rays were emitting light quanta, that light should be monochromatic and hence should not be either Doppler-shifted or deviated. On Einstein's insistence, Hans Geiger (1882–1945) and Walther Bothe (1891–1957) in the Imperial Physical-Technical Institute (*Physikalisch-Technische Reichsanstalt*) in Berlin-Charlottenburg performed this experiment and found no deviation in the beam of light. Their result was discussed intensely by Einstein with Arnold Sommerfeld (1868–1951), Max von Laue (1879–1960), and Paul Ehrenfest (1880–1933). Ehrenfest finally convinced Einstein at the end of January 1922 that this experiment did not constitute a crucial test, after all, between the wave and quantum theories of light.[51]

Raman, far away from Europe in India, had no knowledge of these discussions. He read Einstein's article a few weeks after Ehrenfest, in fact, had settled the issue. But he came to a similar conclusion. In two short articles he suggested that Einstein's experiment could not discriminate between the two theories of light, because when the light is diffracted by the various components of the instrument no Doppler shift was to be expected.[52]

In 1922 Raman also argued that the Einstein-Smoluchowski formula, which is based on the electromagnetic wave theory, and which expresses the scattering power of a medium in terms of its compressibility and refractive index but does not take into consideration the molecular structure of the medium, is qualitatively invalid, because under certain conditions the scattering falls off much more rapidly than predicted.[53] He suggested that one should apply instead the quantum theory of light to explain molecular diffraction. Indeed, in chapter 9 of his monograph, *Molecular Diffraction of Light*, Raman noted the success of Einstein's light-quantum hypothesis in explaining the photoelectric effect and the ionization of gases by X rays.[54] However, in the end he did not take a definite position on the nature of light but said that experiments were underway in his laboratory to determine it.

Raman's Work on the Scattering of Light

In the early 1920s, Raman devoted increased attention to the scattering of light and discontinued his work on acoustics and astronomy. His major motivation apparently was to challenge and reject Lord Rayleigh's theory of the blue color of the sea. In the second half of the nineteenth century, scientists had established experimentally that small particles scatter light of bluish color and that this scattered light is polarized.[55] In 1899 Rayleigh pointed out that the blue color of the sky is due to the scattering of light by air molecules in the atmosphere.[56] He showed that the scattering power is inversely proportional to the fourth power of the wavelength, so that the short wavelengths in the visible spectrum of the sun's light, that is, the blue wavelengths, give the sky its color. A dozen years later, Rayleigh also concluded that the blue color of the sea has nothing to do with the color of water, but is simply the blue of the sky as seen by reflection.[57] Raman read this paper of Rayleigh's in Volume 5 of his *Scientific Papers* and in 1922 disproved

Rayleigh's idea, showing that the blue color of the sea is caused by the diffraction of light by water molecules.[58] For this he made use of the Einstein-Smoluchowski formula and found that the scattering power of a medium, in this case sea water, also varies inversely with the fourth power of the wavelength, thus giving the sea its blue color.

Raman's concern with the nature of light also led him to study experimentally how light is scattered in liquids and crystals and to determine its dependence on the frequency of the light.[59] He further studied the scattering of light in dense vapors and gases, finding that it was not completely polarized as was predicted by theory.[60] The French physicist J. Cabannes suggested that the isotropy of the molecules should be taken into account, while Raman (figure 3) focused on the orientation of the molecules in liquids, developing a qualitative theory that in some cases was able to account for the observed polarization.[61]

One of Raman's collaborators, Kalpathi Ramakrishna Ramanathan (1893–1985), also carried out experiments that Raman later interpreted as crucial to his discovery of the Raman effect. Ramanathan studied the intensity of light scattered by liquids and observed that it was in agreement with theory for moderately anisotropic molecules (water, ethyl alcohol), while it diverged from theory for strongly anisotropic molecules (ether, benzene, toluene).[62] These results led him to examine how the polarization of the scattered light depends on its wavelength, leading him to remark: "Incidentally it is shown that a change previously observed in the imperfection of polarisation with water and alcohol is due to the presence of a *trace of fluorescence* [emphasis added]."[63] Further, "The origin of the fluorescence

Fig. 3. Chandrasekhara Venkata Raman (1888–1970). Courtesy of the Raman Research Institute, Bangalore.

has yet not been definitely ascertained … . In spite of many redistillations, the effect remained practically undiminished."

Raman's use of the term "trace of fluorescence," or "feeble fluorescence,"[64] was directly related to the work of Arthur Holly Compton. As Raman stated later in a lecture to the Faraday Society:

> It will be recalled that Compton was inclined to attribute the softening of X-rays by scattering to what he called "a general fluorescent radiation" until his spectroscopic investigations gave an entirely different version of the matter. It is not surprising, therefore, that the optical effect brought into evidence by the Calcutta investigations was also labeled as a "special type of feeble fluorescence."[65]

Raman and the Compton Effect

In August 1924, Arthur Holly Compton, more than a year after he discovered the Compton effect at Washington University in St. Louis, Missouri, and moved to the University of Chicago, engaged in a second debate with William Duane of Harvard University on the validity of the Compton effect at a meeting of the British Association for the Advancement of Science (BAAS) in Toronto. Raman was present at this debate, and following it, Compton recalled that Raman said to him, "Compton, you're a very good debater; but the truth isn't in you."[66] Raman's statement has been interpreted by Roger H. Stuewer and A. Sur as evidence for Raman's resistence to accept the Compton effect as proof of the validity of Einstein's light-quantum hypothesis.[67] In this section, I will examine the circumstances under which Raman made this statement and show that it cannot be interpreted as opposition to Compton's discovery. I thus will show that well before Raman discovered the Raman effect he accepted the quantum nature of light.

At the BAAS meeting in Toronto, William Duane gave a paper entitled, "On Secondary and Tertiary Radiation,"[68] in which he reported on experiments that he had carried out with Samuel K. Allison, George L. Clark, and William W. Stifler at Harvard. Duane argued that the change in wavelength that Compton had observed "must be due to fluorescent radiation generated in the crystal itself by X-rays of much shorter wave-lengths." He thus opposed Compton's quantum interpretation and attributed the change in wavelength to a secondary effect. Eventually however, after Compton visited Duane's laboratory, Duane changed his mind and accepted Compton's experimental results and interpretation.[69]

Compton also gave a paper at the Toronto BAAS meeting entitled, "The Quantum Theory of the Scattering of X-rays,"[70] whose content is evident although there is no abstract or summary of it in the report of the meeting. Joseph A. Gray also gave a paper entitled, "Scattering of X- and Gamma-rays and the Production of Tertiary X-rays," in which he argued that: "Experiments with X-rays show that the proportion of scattered rays of longer wave-length than the primary is independent of the crystalline structure and thickness of the radiator … . Results of the scattering of γ-rays do not altogether agree with the quantum theory of scattering … . If X-rays consist of quanta, they should have a range. If this is the case, in the writer's opinion *the wave theory should be abandoned* [emphasis added]."[71] The reporter for *Nature* did not note a similar attitude on Compton's part,[72] nor did Compton argue for the abandonment of the wave theory in his original paper. Rather, he hoped for a reconciliation of the wave and quantum theories of light, noting that "the problem of scattering is so closely allied with those of reflection and interference that a study of the problem may very possibly shed some light upon the difficult question of the relation between interference and the quantum theory."[73]

Like Compton, Raman was impressed with the past success of the electromagnetic wave theory in explaining interference and diffraction phenomena. Thus, at the BAAS meeting, according to the reporter for *Nature*, Raman made an "eloquent appeal against a too hasty abandonment of the classical theory of light."[74] In general, Raman believed that "theories must stand or fall according to as they agree with the facts, and not vice versa,"[75] and since Compton's quantum theory of scattering agreed with the experimental facts, Raman would not have objected to it. How then can we explain the contrary recollections of Compton? Certainly he would have been fascinated with Raman as one of the very few non-European physicists present at the Toronto meeting, and wearing a turban too. As we shall see, however, he evidently misinterpreted Raman's remark: Raman's objections were not directed against light quanta or Compton's experiments but were of a more technical nature.

Thus, in 1927, Raman discussed Compton's discovery and his recently published book, *X-Rays and Electrons*, as follows:

> As is well known, there is an addition to the X-ray scattering of degraded frequency, an unmodified secondary radiation the existence of which has been explained by Prof. Compton as due to the whole group of electrons in the atom scattering conjointly. To this view, the objection might be raised that if one electron acting alone can scatter a quantum, and also all the Z electrons in the atom acting together, then why do we not observe scattering by two, three, or more electrons acting together at a time, with their corresponding fractional Compton shifts in wavelength? To the alternative explanation of the unmodified scattering given by Profs. Compton and [George E. M.] Jauncey that it represents the scattering by an electron which the impinging quantum is unable to detach from the atom, the equally pertinent query may be asked, then why is the intensity of this type of radiation proportional to Z^2 and not to Z?[76]

Raman went on to emphasize the success of Maxwell's theory in explaining interference and scattering of light by solids, liquids, and gases under a wide range of conditions, and then asked, as he had at the Toronto BAAS meeting, "Is it conceivable … that Maxwell's theory and thermodynamics taken together would fail in the closely allied field of X-ray research?"[77] Thus, Raman sought to explain the Compton effect classically, and indeed in 1928 he derived the change in wavelength on the basis of the classical wave theory.[78] Moreover, he and C. M. Sogani constructed an absorption photometer to study the Compton effect experimentally,[79] which also leaves no doubt that Raman accepted Compton's results before he discovered the Raman effect.

Let us therefore revisit the Compton-Raman episode at the Toronto BAAS meeting in 1924. Compton referred to it in his "Personal Reminiscences," which were published in 1967, five years after his death. He there recalled his debate with Duane, noting:

> After discussing it for a solid afternoon, we decided to call the debate a draw. The result was summarized by a comment of C. V. Raman, who was visiting Toronto at the time. As we left, he said to me, "Compton, you're a very good debater; but the truth isn't in you."[80]

Compton added: "I think it was probably these discussions that led him to discover the Raman effect two year later, which was essentially a very similar phenomenon that was observed in the field of light." That Compton thus gives the year of Raman's discovery as 1926 instead of 1928 suggests that we should treat his recollections cautiously.

This is supported by the somewhat different recollection of the Compton-Raman episode by Compton's wife, Betty McCloskey Compton. In an interview in 1968, although she could not at first remember Raman's name, she stated:

> Anyway he [Raman] was very dark, just as black as could be, but he had a beautiful Scotch accent. He would be asking questions from the back of the hall, and it was so disconcerting to have this person, black as coal, with this beautiful Scotch accent. He was the one who said, "Compton, you answer questions well; you're a good debater, but the truth isn't in you."[81]

When she then was asked if Compton had won the debate, she replied:

> No, it was nip and tuck at that time. Raman had said, "well, you seem to be able to answer the questions but I don't believe it." *Afterwards he practically apologized for that*. He said, "*Oh Compton, that was in the heat of the discussion. I really didn't mean that* [emphasis added]."[82]

Thus, the extent to which Raman opposed Compton in Toronto is uncertain. We do know, however, that Compton's winning of the Nobel Prize in 1927 was a crucial stimulous to Raman. As Raman noted shortly after he discovered the Raman effect in 1928:

> Early this year … a powerful impetus to further research was provided when I conceived the idea that the effect [I just discovered] was some kind of optical analogue to the type of X-ray scattering discovered by Prof. Compton, for which he recently received the Nobel Prize in Physics. I immediately undertook an experimental re-examination of the subject in collaboration with Mr. K. S. Krishnan and this has proved very fruitful in results.[83]

The Discovery of the Raman Effect

The velocity of light in a medium depends upon its index of refraction, which in turn depends upon the wavelength of the light, a process known as dispersion. In 1922 the English theoretical physicist Charles G. Darwin (1887–1962) attempted to explain dispersion, unsuccessfully, on the basis of quantum theory.[84] The following year the Austrian theoretical physicist Adolf Smekal (1895–1959) assumed that light has a quantum structure and showed that scattered monochromatic light would consist of its original wavelength as well as of higher and lower wavelengths.[85] He derived a dispersion formula by exploiting Bohr's correspondence principle, that is, by assuming that the dispersion produced by an atom in a high quantum state is the same in both the classical and quantum theories. Only in 1924–1925 was a full and satisfactory quantum-theoretical explanation of dispersion provided by Hendrik A. Kramers (1894–1952) and by Kramers and Werner Heisenberg (1901–1976), which formed the immediate background to Heisenberg's discovery of matrix mechanics.[86] Other prominent physicists also contributed to the understanding of dispersion at this time.[87] Nevertheless, none of this theoretical work, and in particular Smekal's prediction of the appearance of higher and lower wavelengths when monochromatic light is scattered, exerted a direct influence on the discovery of the Raman effect.

Evidence for such an effect was published in July 1928 by the Russian physicists Grigorii Samuilovich Landsberg (1890–1957) and Leonid Isaakovich Mandelstam (1879–1944),[88] who were studying Albert Einstein's and Peter Debye's theories of the specific heats of solids. They concluded that when light of frequency ν is scattered by a crystal, it would not only be diffracted by the Debye elastic waves acting as a grating, it also would experience a frequency shift $\Delta\nu$ caused by the elastic waves propagating at the velocity of sound. Searching for this frequency shift in quartz, they observed that it was different from what they had expected, which they took to mean that they had discovered a new phenomenon. They were uncertain of its explanation, however. One possibility was that while being scattered, the light lost energy by exciting infrared frequencies in the quartz crystal, thereby diminishing the frequency of the light.

In India, Raman and K. S. Krishnan made their discovery while searching for an optical analogue of the Compton effect. Raman noted in his first report[89] that in 1922 he and his student K. Seshagiri Rao had observed the depolarization of water as a function of wavelength, which changed, for example, by 13.2, 10.2, 11.5, 15.3, and 21.7 percent for red, yellow, green, blue, and violet light. Three years later, K. S. Krishnan observed, as K. R. Ramanathan had before him, a "feeble fluorescence" when light was scattered by various liquids (water, ether, monohydric alcohols, benzyl and benzol chlorides, methyl ethyl ketone, diethyl ketone, butyric acid, and acetaldehyde).[90] Attempts to determine the spectrum of this "feeble fluorescence" during the following years failed, because its intensity was too low.[91] (Recent experiments with a laser have shown that only a tiny fraction of light, 1 part in 10^8, experiences a change in frequency when scattered.[92]) Thus, in the event, very long exposure times were required to take spectra. The Russian physicists, for example, reported exposure times of 2 to 14 hours and 100 hours under different

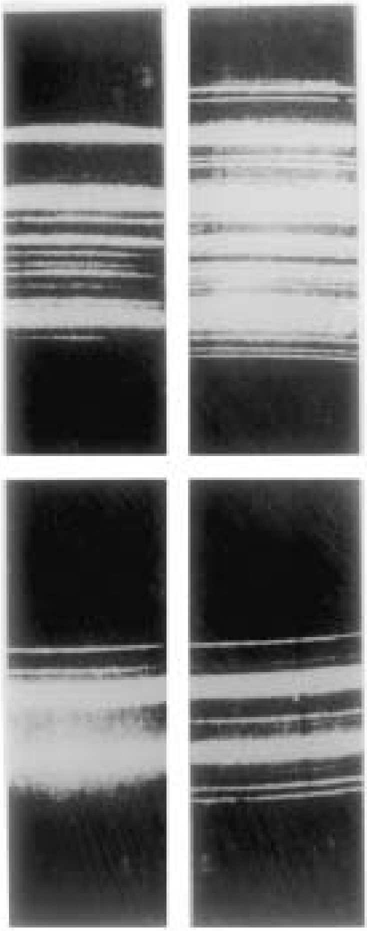

Fig. 4. The first spectra taken by C. V. Raman and K. S. Krishnan. The upper-left photograph shows the incident light consisting of the spectrum of a quartz mercury arc lamp after passing through a blue filter that cuts out all wavelengths greater than the indigo line at 4358 Ångstroms. The upper-right photograph shows the same spectrum when scattered by liquid benzene and taken with a small Adam Hilger spectroscope. Note the appearance of modified lines owing to the Raman effect. The lower-left and the lower-right photographs show the same effect using a different filter. Courtesy of the Raman Research Institute, Bangalore.

conditions for crystals.[93] Later, for vapors, exposure times of more than 180 hours were required.[94] Raman first displayed spectra showing a change of frequency during a lecture he gave at a meeting of the South Indian Scientists Association on March 16, 1928 (figure 4).[95] In all, he and Krishnan had observed scattered secondary radiation of smaller frequency in 60 liquids and vapors.[96] Because the scattered light was of relatively high intensity and was polarized, they could rule out the possibility that it was fluorescent radiation.

Prior to the above lecture, Raman sent two short articles to *Nature* (one written jointly with Krishnan),[97] which he signed on February 16 and March 8, 1928, respectively, and which appeared in print before the first publication of the Russian physicists, which was communicated to *Die Naturwissenschaften* on May 6, 1928, and appeared in July 1928.[98] Raman's articles in *Nature* did not display any spectra; they first appeared in print when his lecture of March 16, 1928, was published in the *Indian Journal of Physics*.[99] He sent reprints of that article reporting his discovery to 2000 scientists in France, Germany, Russia, Canada, and the United States.[100]

Reception

The first person to take note of Raman's discovery was the French scientist Yves Rocard (1903–1992), who published a paper on it in the April 23, 1928, issue of the *Comptes rendus* of the *Académie des Sciences*.[101] In Germany, it seems that Raman's discovery was known only through Raman's short articles in *Nature* and not through his article in the *Indian Journal of Physics* that contained his spectra, which led to some speculation about his discovery. Thus, the German theoretical physicist Georg Joos (1894–1959) wrote from Jena to Arnold Sommerfeld in Munich on May 14, 1928, asking, "Do you think that Raman's work on the optical Compton effect in liquids is reliable? … The sharpness of the scattered lines in liquids seems doubtful to me."[102] Although Raman's experiments could not be repeated successfully in Munich, Sommerfeld (figure 5) nevertheless replied to Joos on June 9, 1928, that: "In my opinion Raman is correct … . He writes to me, that the difference between the lines is exactly equal to the infrared frequencies of the molecules under consideration."[103]

In Berlin, the German experimental physicist Peter Pringsheim (1881–1963) repeated Raman's experiments successfully and sent his spectra to Sommerfeld on June 20, 1928, thus vindicating Sommerfeld's belief in the validity of Raman's work. Pringsheim then reported his work in two articles the following month,[104] becoming the first person to coin the terms "Raman effect" and "Raman lines." In 1929 Pringsheim contributed an article on the Raman effect to the *Handbuch der Physik*,[105] just as Joos contributed one to the *Handbuch der Experimentalphysik*.[106] In 1930 Clemens Schäfer and Frank Matossi contributed yet another article on the Raman effect to the *Fortschritte der Chemie*, *Physik und Physikalische Chemie*,[107] here emphasizing its importance for chemistry. In 1931, K. W. F. Kohlrausch published a book that contained 417 references on what he called, perhaps chauvinistically, the Smekal-Raman effect.[108] Most of the papers that were published on the Raman effect between 1928 and 1937 were published in Germany and Austria.[109]

The Nobel Prize

Raman received the Nobel Prize in Physics for 1930 "for his work on the scattering of light and for the discovery of the effect named after him."[110] He received the

Nobel Prize only two years after he made the discovery, and he was the first Asian to be so honored. There seems to be three major reasons why the Russian physicists, Landsberg and Mandelstam, did not share the Nobel Prize with Raman, even though they discovered the effect almost simultaneously with Raman.[111] First, no less than ten physicists from several countries nominated Raman for the Nobel Prize, while only two Russians nominated Landsberg and Mandelstam for it. Thus, the scientific community at large credited Raman with the discovery. Second, Raman published his results earlier than the Russians, who in fact cited Raman's work, so that the Nobel Committee did not believe that the Russians had obtained their results independently. Third, the Nobel Committee felt that Raman's experiments, since they involved solids, liquids, and gases, had established the universality of the effect.[112]

Conclusions

I have shown that Raman initiated experiments as early as 1922 in an attempt to determine if light was of a wave or a quantum nature. He interpreted his results successfully in terms of the Einstein-Smoluchowski formula, which was based on Maxwell's electromagnetic wave theory, and which led him to believe that there was

Fig. 5. Arnold Sommerfeld (middle) visited the Indian Association for the Cultivation of Science in Calcutta in October 1928 and posed with K. S. Krishnan (left) and C. V. Raman (right). Courtesy of the Raman Research Institute, Bangalore.

no need to abandon that theory. I then argued that Raman did not object to Compton's discovery of the Compton effect because Compton interpreted it on the basis of light quanta, but for more technical reasons. Raman's remarks to Compton at the BAAS meeting in Toronto in 1924 thus should not be interpreted as resistance to Einstein's light-quantum concept, even though Raman later derived the Compton wavelength shift on the basis of the electromagnetic wave theory.

Raman's work on light scattering led him to his discovery of the Raman effect, which then was seen as a confirmation of Smekal's prediction that when monochromatic light is scattered by a transparent medium the scattered light will also contain both higher and lower frequencies. In general, Raman, like other Indian scientists, worked in isolation and had to rely largely on his own knowledge and experiments. In Germany, Sommerfeld accepted Raman's discovery, and Pringsheim repeated Raman's experiments successfully, which overcame skepticism towards Raman's results. In the end, Raman was accorded priority for the discovery over the Russians Landsberg and Mandelstam, and a large number of physicists nominated him for the Nobel Prize in Physics for 1930.

Acknowledgments

I thank Falk Riess, University of Oldenburg, for valuable discussions and help with this article. I am grateful to Roger H. Stuewer for valuable comments on an early version of this paper and for his careful editorial work on it. I thank the following institutions and individuals for sources on which this article is based: the American Institute of Physics for Betty McCloskey Compton's interview; the Asiatic Society of Bengal for Raman's correspondence; the Indian Institute of Astrophysics (D. C. V. Mallik) for the *Journal of the Astronomical Society of India*; the Deutsches Museum in Munich for Sommerfeld's letters; Churchill College, Cambridge, for A. Mookerjee's letter; the Nehru Memorial Library in Delhi for Saha's correspondence; the Niels Bohr Archive in Copenhagen for Raman's letter; the Raman Research Institute for photographs, newspaper clippings, and Raman's convocation lecture; and the Royal Society of London for Raman's nomination letter and M. O. Foster's document. I am obliged to a well-wisher (who desires to remain anonymous) for a copy of Bose's letter. I am thankful to Santimay Chatterjee, Calcutta, who sent me articles from *The Illustrated Weekly of India* and the *Indian Physical Society – Diamond Jubilee*. Finally, I am grateful to the Heinrich Böll Stiftung in Berlin for financial support while writing this article.

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